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# Testing Massive Star Formation Theory in Orion

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**Abstract.** I compare theoretical models of massive star formation with observations of the Orion Hot Core, which harbors one of the closest massive protostars. Although this region is complicated, many of its features (size, luminosity, accretion disk, H II region, outflow) may be understood by starting with a simple model in which the star forms from a massive gas core that is a coherent entity in approximate pressure balance with its surroundings. The dominant contribution to the pressure is from turbulent motions and magnetic fields. The collapse can be perturbed by interactions with other stars in the forming cluster, which may induce sporadic enhancements of the accretion and outflow rate.

## 1. Theoretical Models of Massive Star Formation

Stars much more massive than the Sun, although rare, are important for the energetics and metal production of galaxies. How do these stars assemble themselves from the interstellar medium (ISM)?

Observationally it is clear that massive stars are born in the densest *clumps* of gas inside giant molecular clouds (GMCs) (e.g. Mueller et al. 2002), which undergo quite efficient ($\sim 10 - 50\%$) transformation to star clusters. The new stellar mass is mostly in low-mass stars, and it appears that the majority of Galactic star formation occurs in this clustered mode (Lada & Lada 2003). This concentration of star formation in a relatively small part of the total Galactic molecular ISM, suggests that the creation of clumps may be triggered by processes external to GMCs. One possibility is an origin in local regions of pressure enhancement created in GMC collisions (Tan 2000). An alternative to triggering is the gradual condensation of clumps in regions of GMCs that become sufficiently self-shielded from the Galactic far UV background (McKee 1989).

This question can be addressed by studying the infrared dark clouds (IDCs) (e.g. Egan et al. 1998), which are the likely precursors of star-forming clumps. The collisional model predicts IDCs are surrounded by coherent, supersonic ($\sim 10\mathrm{km\ s^{-1}}$) flows. Teyssier et al. (2002) report significant velocity structure towards all their IDCs, and in at least one case the gas is spatially connected across this velocity range. Since the angular momentum vectors of collisions in a thin shearing disk can be both parallel and anti-parallel to that of the host galaxy, the collisional model can account for the almost equal proportions of pro- and retrograde GMC rotations in M33 (Rosolowsky et al. 2003). The dependence of collision rate on shear leads to reduced star formation efficiency in galaxies with rising rotation curves — a general trend of the Hubble sequence.

In this article I focus on the separate question of how clumps, once formed, transform a small part of themselves into massive stars. Clumps can be regarded as quasi-virialized structures: virial mass estimates are similar to estimates of the total gas and stellar mass (Plume et al. 1997); and their mor-

phologies are often close to spherical (Shirley et al. 2003). The virial velocity is typically several km $\mathrm{s}^{-1}$, while strong cooling to $\sim 10$ K causes the sound speed to be only $c_{\rm th} = 0.19(T/10{\rm K})^{1/2}{\rm km\ s^{-1}}$ (for $n_{\rm He} = 0.2 n_{\rm H_2}$). Thus the clumps are supersonically turbulent. Measured magnetic field strengths are $\sim$ mG (Crutcher & Lai 2002). The Alfvén velocity, $v_A = B/(4\pi\rho_0)^{1/2} = 1.84(B/{\rm mG})(n_{\rm H}/10^6{\rm cm^{-3}})^{-1/2}{\rm km\ s^{-1}}$, is comparable to the virial velocity.

Turbulence and self-gravity engender the clumps with substructure, the nature of which is under intense numerical study (see Mac-Low & Klessen 2003 for a review). Self-gravity tends to cause condensations on the scale of the Jeans mass, which can be generalized to include nonthermal forms of pressure support. Turbulence leads to compression of gas into filaments and sheets. The combination may be enough to produce the observed mass spectrum of cores, which appears to be similar to the stellar mass function (e.g. Motte et al. 2001). Massive, quiescent cores are seen in Orion (e.g. Li, Goldsmith, & Menten 2003).

## 1.1. Formation from Direct Collapse of Gas Cores

The rate of collapse of gravitationally unstable gas cores is set by their initial density profile. Singular isothermal spheres, described by the Shu solution for inside-out collapse, have a constant accretion rate, $\dot{m}_* = 0.975 c_{\rm th}^3/G = 1.54\times10^{-6}(T/10{\rm K})^{3/2} M_\odot\ {\rm yr^{-1}}$, which is directly related to the local enclosed mass divided by the local free-fall timescale: $\dot{m}_* = \phi_* m_*/t_{\rm ff}$, with $\phi_* = 0.663$. The collapse of uniform spheres, described by the Larson-Penston solution, has a value of $\phi_*$ that is about 50 times larger. Bonnor-Ebert spheres have nonsingular centers, that locally approximate uniform density, so their initial collapse rate is relatively high, but then evolves towards the Shu solution. For pressure-confined clouds, as the pressure is raised, the size of the equilibrium cloud contracts, thus increasing its mean density and accretion rate. The above results apply in a similar manner for the more general case of cores with polytropic equations of state. Differences in the density profile with respect to the $r^{-2}$ law of the singular isothermal sphere, lead to departures from a constant accretion rate: e.g. a shallower profile leads to a growing accretion rate.

Myers & Fuller (1992) and McLauglin & Pudritz (1997) considered various models for the density structure of massive star-forming cores, but normalized them to be in equilibrium in a medium of quite low pressure. Formation timescales could then be $\gtrsim 10^6$ yr, a significant fraction of the main sequence stellar lifetime and probably inconsistent with the relative small spread in ages seen in young star clusters (Palla & Stahler 1999). Osorio, Lisano, & D'Alessio (1999) considered collapse with higher accretion rates, but with the normalization set via an empirical modeling of the infrared spectra of the gas envelopes.

McKee & Tan (2003, hereafter MT) approximated the structure of massive gas cores that are about to undergo collapse to stars with pressure-truncated singular polytropic spheres, including the effect of a thermal core. The particular equation of state ($P = K\rho^{\gamma_p}$, with $\gamma_p = 2/3$) was chosen so that the equilibrium density profile matched observed profiles of *clumps* ($\rho \propto r^{-1.5}$), and it was assumed that the same density structure applied on the smaller scales of cores. The cores are bounded by the mean pressure in the clump, which is estimated assuming clumps are in approximate hydrostatic and virial equilibrium, so that $P \simeq G\Sigma^2$, where $\Sigma$ is the surface density. Typical observed values are $\Sigma \sim 1\ {\rm g\ cm^{-2}}$ for clumps forming massive stars (Mueller et al. 2002).

Now consider the properties of a core of a given mass, $M$, that will soon collapse to form a star. The equilibrium radius is $r_c = 0.057 M_{60}^{1/2} \Sigma^{-1/2}$ pc, where $M_{60} = M/60 M_\odot$. Cores are very concentrated, which alleviates the crowding problem of formation in stellar clusters: the central stellar density in the Orion Nebula Cluster (ONC) is $\sim 10^4\,\mathrm{pc}^{-3}$, giving a stellar separation of about 0.05 pc.

Note that the assumption the core collapse starts in the equilibrium state is an idealization. Cores probably form and become unstable at the confluence of turbulent flows, and so may be somewhat out of equilibrium. However we expect that the deviations should generally be rather modest, as the turbulent motions are not much greater than the Alfvén speed and as magnetic fields, both tangled and ordered, are important sources of pressure support.

The velocity dispersion at the core surface is $1.27 M_{60}^{1/4} \Sigma^{1/4}$km s$^{-1}$. The minimum equilibrium core mass, the Bonnor-Ebert mass where thermal pressure dominates, can be estimated by setting this speed equal to the sound speed. This mass is $0.0504 (T/20\mathrm{K})^2 \Sigma^{-1} M_\odot$, which is comparable to the mass at which the ONC mass function rapidly decreases (Muench et al. 2002).

The rate of core collapse is $\dot{m}_* = 4.6 \times 10^{-4} f_*^{1/2} M_{60}^{3/4} \Sigma^{3/4}\ M_\odot\ \mathrm{yr}^{-1}$, where $f_*$ is the ratio of $m_*$ to the final stellar mass and 50% formation efficiency is assumed. Feeding a star and disk at such high rates may strongly influence the star formation process. For example, in the limit of spherical accretion, Wolfire & Cassinelli (1987) pointed out that the ram pressure of infalling gas at the dust destruction front could overcome radiation pressure from a high-mass star.

The collapse time, $1.3 \times 10^5 M_{60}^{1/4} \Sigma^{-3/4}$ yr, is short and quite insensitive to $M$. This allows coeval star formation in clusters, consistent, for example, with the estimated 1 Myr formation timescale of the ONC (Palla & Stahler 1999).

If the core starts with a rotational to gravitational energy ratio $\beta$, then a disk forms at a centrifugal radius of about $r_{\mathrm{disk}} = 1200 (\beta/0.02)(f_* M_{60})^{1/2} \Sigma^{-1/2}$AU, assuming solid body rotation of the core. We have normalized to a typical value of $\beta$ inferred in cores of lower mass and density (Goodman et al. 1993).

Disk accretion is expected to be accompanied by an outflow of material at a rate $\dot{m}_w \equiv f_w \dot{m}_*$, with $f_w \simeq 0.1 - 0.4$, and a velocity $v_w = f_v v_K = 920 (f_v/2.1)(m_*/10 M_\odot)^{1/2} (r_*/10\ R_\odot)^{-1/2}$km s$^{-1}$, with e.g. $f_v \simeq 2.1$ (Shu et al. 2000), and where $v_K$ is the Keplerian speed at the star. A bipolar outflow is created perpendicular to the disk, which should maintain its orientation over much of the star formation timescale, unless the disk is perturbed by a companion, passing star, or warping instability. Note that if many stars are forming together in a cluster, then multiple outflows are inevitable (Tan & McKee 2002), and their effects must be disentangled.

Thus key signatures of this star formation model are the presence of coherent gas cores, that contain protostellar disks, from which outflows are driven and maintained for many local dynamical timescales. Our (Tan & McKee) recent research program has focused on trying to quantify the properties of these elements of the model for comparison to observations.

### 1.2. Formation via Competitive Accretion and/or Stellar Collisions

A number of objections to the core accretion model have been raised. Theoretically, there is the problem of radiation pressure preventing accretion to a massive, luminous protostar (Larson & Starrfield 1971; Wolfire & Cassinelli 1987). A disk

geometry may help (e.g. Nakano 1989; Yorke & Sonnhalter 2002). Observationally, it appears that massive stars tend to form in crowded regions near cluster centers (Bonnell, & Davies 1998) and in binaries where the secondary is relatively massive compared to a random sampling from the IMF (Eggleton, Tout, & Fitchett 1989). Relatively large numbers of massive stars are "runaways", perhaps ejected from dynamical interactions in young star clusters (Gies 1987).

These points have motivated formation models based on protostellar collisions and competitive Bondi-Hoyle accretion. Bonnell, Bate, & Zinnecker (1998) presented a model in which extreme stellar densities result in a cluster of lower-mass stars that dissipate their kinetic energy as they accrete from the initially dominant gaseous component of the protocluster. For the collisional timescale to become short enough to be relevant to the formation process the stellar density must reach at least $\sim 10^6 - 10^8\,\mathrm{pc}^{-3}$, several orders of magnitudes greater than the observed central density of the ONC. Bonnell & Bate (2002) presented SPH simulations of the collapse of an isothermal gas clump initially seeded with many low-mass stars. With a collision radius of 2 AU, they found that the most massive star that formed did increase its mass significantly in several merger events. However, the large increase in density after one clump free-fall time, when much of the growth occurs, is probably an artifact of the initial conditions: i.e. the cold, synchronized collapse of a system that has about a 1000 Jeans masses. Bonnell, Bate, & Vine (2003) presented more realistic calculations with turbulent initial conditions, but still isothermal and unmagnetized. While collisions were no longer important for massive star formation, it was claimed that close dynamical interactions were common for these stars during their formation.

## 2. Unraveling Orion

We focus on the Orion Hot Core region, which includes the Kleinmann-Low Nebula (Fig. 1), $\sim 0.1$ pc NW in projection from the Trapezium stars at the heart of the Orion Nebula Cluster (ONC), about 450 pc distant. The Hot Core region has a total luminosity $\sim 10^5\,L_\odot$ (Gezari, Werner, & Backman 1998, hereafter G98). The brightest $2\mu$m source is the Becklin-Neugebauer (BN) object, which is also a thermal radio source. A second thermal radio source, "I", is located close to the center of the densest region of gas, as traced by depth of the silicate absorption (G98). A weaker radio source, "n", is nearby (Menten & Reid 1995) but does not appear to be particularly luminous (G98).

X-ray observations can provide a census of lower mass stars (Garmire et al. 2000), with a $\sim 50$ ks Chandra observation sensitive to X-rays from protostellar sources down to $A_V \sim 60$ ($N_\mathrm{H} \sim 10^{23}\,\mathrm{cm}^{-2}$). Emission is detected 500 AU NW of BN and coincident with "n", but not from "I". Including "n", there are 9 sources within $10''$ of source "I", all S and E of the NE-SW axis. Only two do not have optical or near IR counterparts, and these are both about $9''$ away. Taking a stellar surface density of $4000\,\mathrm{pc}^{-2}$ for the larger scale distribution of stars (Hillenbrand & Hartmann 1998), we expect about 6 sources in this region, so the stellar density is somewhat enhanced. If half of the 9 sources are really within 4500 AU of "I", then the local stellar density is $10^5\,\mathrm{pc}^{-3}$. This estimate is uncertain because of Poisson statistics and source incompleteness, but is far below the level at which stellar collisions are important.

Scoville et al. (1983) noted that the systemic velocity of BN and its nebula was $+21\mathrm{km\ s}^{-1}$, i.e. $+12\mathrm{km\ s}^{-1}$ relative to the molecular cloud. Plambeck et

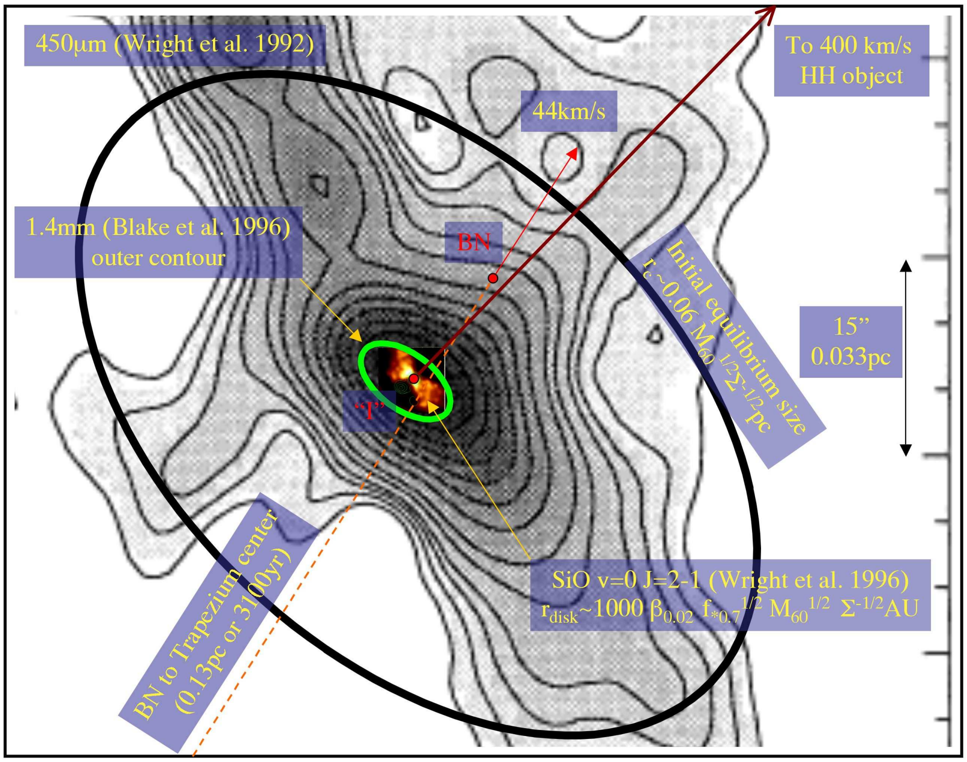


Figure 1. Schematic of Orion Hot Core region.

al. (1995) measured the proper motion of BN with respect to "I" with a 9 year baseline. From this and more recent data (Plambeck, private communication), we estimate a velocity of about 42 km $s^{-1}$ in the plane of the sky towards position angle $-33°$, i.e. directly away from the Trapezium and "I". This gives a total velocity of 44 km $s^{-1}$. This motion may explain the 500 AU displacement of the X-ray emission. BN would have made closest approach to "I" about 460 yr ago, and would have been at the center of the Trapezium 3100 yr ago. Together with its estimated luminosity of 2500-$10^4$ $L_\odot$ (B98), we conclude that BN is a runaway B3-B4 (8-12$M_\odot$) star, perhaps ejected from the Trapezium region. Close passage near "I" may have triggered enhanced accretion (and outflow) several hundred years ago, depending on their line-of-sight separation.

The polarization vectors of 3.8 $\mu$m emission suggest that a spatially concentrated source near "I" is responsible for much of the Hot Core region luminosity (Werner, Capps, & Dinerstein 1983). If this is a single protostar, then the luminosity implies a mass of $\sim 20M_\odot$ (MT). We do not expect star formation from a core to be 100% efficient, so the initial mass in the region of the core that has now collapsed was probably larger, perhaps by a factor of two. There is still a comparable mass of gas around the protostar that is still infalling. Thus as a working model for the system, we consider an initially $60M_\odot$ core, about 2/3 of which has already collapsed. The bounding ambient pressure is influenced by the self-gravity of gas in the clump (that has partly formed the $\sim 1000M_\odot$ ONC) and by the pressure from feedback from the massive Trapezium stars. We shall consider the case that the pressure is equivalent to that due to self-gravity in the central region of a clump with $\Sigma = 1$ g $cm^{-2}$.

First consider the size of the initial core: it is $\sim 0.06$ pc (12,000 AU, 26″) in radius. In the models of MT, the cores were somewhat flattened due to a component of large scale magnetic field support. An outline of the theoretical core is shown in Fig. 1, superposed with the 450 $\mu$m (8″) map of Wright et al. (1992). The sizes are comparable, with the observed core being about twice as concentrated, as might be expected midway through its collapse. When constructing core spectra, care should be taken that the regions probed at different wavelengths probe the same scales: e.g. the radial extent of the outer contour in the 1.4 mm map of Blake et al. (1996) is only $\sim 1800$ AU from "I".

For $\beta = 0.02$, the disk size at this stage in the collapse is about 1000 AU, comparable to the extent of emission in the 1.4 mm continuum (Blake et al. (1996) and SiO (v=0; J=2-1) maser line (Wright et al. 1995). Indeed, Wright et al. interpreted the maser emission as tracing a disk. Comparing the spectra of the emission peaks of approaching and receding sides, separated by about 1″, most emission is in the range $-6$ to $+14$km s$^{-1}$. For an inclination angle of the disk rotation axis to our sight line of 65° (below), the true velocity difference is then about 22km s$^{-1}$. The enclosed mass inside $\sim 200$ AU is thus $\simeq 30 M_{\odot}$.

SiO (v=1) maser transitions probe conditions of higher density ($n_{\rm H} \sim 10^{10\pm1}$ cm$^{-3}$) and temperature ($T \gtrsim 10^3$ K), and are seen on scales $\sim 50$ AU (e.g. Doeleman, Lonsdale, & Pelkey 1999), and may trace an outflow along the NW-SE axis (Greenhill et al. 1998; however, see Greenhill et al. 2003).

Tan & McKee (2003, hereafter TM) presented a model for the density structure of the outflow from a massive protostar, including a low-density cavity along the rotation axis. With parameters $m_* = 20 M_{\odot}$ and $\dot{m}_* = 10^{-4} M_{\odot}$ yr$^{-1}$, the density near the cavity and within $\sim 100$ AU of the star is $n_{\rm H} \sim 10^{8-9}$cm$^{-3}$. This gas is heated and ionized by the protostar, which may be close to the main sequence. Thermal bremsstrahlung emission from this *outflow-confined H* II *region* explains the observed radio spectrum, and the derived ionizing luminosity is consistent with protostellar evolution models. In fact "I" appears elongated along the outflow axis at 22 and 43 GHz (Menten & Reid, in prep.).

The outflow speed should be about the protostellar escape speed, and in the model of TM is $\simeq 1000$km s$^{-1}$. The on-axis, well-collimated part of the flow, with line-of-sight velocities of $\simeq 400$km s$^{-1}$ (for inclination angle of 65° adopted by TM), should reach quite far from "I". Taylor et al. (1986) observed $\sim 300-400$km s$^{-1}$ blue-shifted OI from Herbig-Haro objects about 1'(0.13 pc) to the NW. Note that these velocities are much greater than those probed by current maser observations near "I". We predict that faster maser velocities will be found if the search region is expanded to higher (blue and red shifted) velocities. In this model, individual spots with proper motion of only $\sim 10$km s$^{-1}$ must be decoupled and almost stationary with respect to the gas flow.

The outflow is collimated, but not as a narrow jet: each logarithmic interval in angle from the axis (cavity excluded) delivers about equal momentum (Matzner & McKee 1999). This flow interacts with the surrounding turbulent and clumpy gas core, reducing the collapse efficiency and sweeping up molecular gas to a range of slower velocities. On scales of $\sim 10''$ from "I", Stolovy et al. (1998) report clumpy $H_2$ emission with line widths up to $\sim \pm 100$km s$^{-1}$. We estimate a total momentum injection $p_w \simeq 4500 (m_*/20 M_{\odot})^{1.4} M_{\odot}$km s$^{-1}$. Depending on the ambient density, the wind may have penetrated quite far in

the clump. Within a few tenths of a parsec, dense gas traced by $NH_3$ (Wiseman & Ho 1998) lies in filaments perhaps sculpted by an outflow from "I". In this case there should be many gas clumps, stars, and protostars in the flow. The "bullet+wake" features (Allen & Burton 1993) are hard to understand in this context. They may be related to the development of a thin-shell instability where the outflow has swept up relatively uniform material (Stone et al. 1995). The outflow rate may be highly variable, e.g. close passage of BN to "I" may have tidally triggered enhanced accretion and outflow several hundred years ago.

## 3. Conclusions

An extension of low-mass star formation models, based on the collapse of gas cores, to massive systems, can account in broad terms for many of the observed features of the Orion Hot Core region, including the core size, luminosity, accretion disk, compact H II region, and fast outflow. The situation is somewhat complicated by the presence of other stars in the ONC: e.g. tidal interactions with other stars, such as BN, may have led to sporadic enhancements in the accretion and outflow. However, most stars are of low mass and have little influence on the collapse. Also the formation of the ONC is relatively advanced, and these effects would have been less common for massive stars forming in the earlier stages. We conclude that the Orion Hot Core protostar provides good evidence in support of massive star formation from coherent gas cores that become gravitationally unstable at relatively large masses. These cores are rare both in terms of their number and in the fraction of the total clump mass they contain. Numerical simulation of the details of their formation from a turbulent, magnetized, and self-gravitating medium is an important goal.

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